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An alternative method of evaluating 1540nm exposure laser damage using an optical tissue phantom

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ABSTRACT

An optical phantom was designed to physically and optically resemble human tissue, in an effort to provide an alternative for detecting visual damage resulting from inadvertent exposure to infrared lasers. The phantom was exposed to a 1540-nm, Erbium:Glass, Q-switched laser with a beam diameter of 5 mm for 30 ns at varying power levels. Various materials were tested for use in the phantom; including agar, ballistic media, and silicone rubber. The samples were analyzed for damage lesions immediately after exposure and the Minimum Visible Lesion – Estimated Dose 50% (MVL-ED₅₀) thresholds were determined from the data. In addition, any visible damage was evaluated for similarity to human tissue damage to determine if the phantom tissue would be a suitable substitute for *in vivo* exposures.

Keywords: Er:Glass, phantom, epoxy resin, ballistic media, agar, ED₅₀, skin, damage, tissue, laser damage

1. INTRODUCTION

Tissue phantoms are becoming a widely used method of evaluating various laser applications. Not only do they reduce the need for human and animal test subjects, phantoms also provide a uniform sample material without the variables introduced by biological subjects. The objective of this experiment was to create a low-cost material that would be easily reproduced and that closely resembled the optical and physical characteristics of human or porcine skin. In addition, it must be able to meet the rigorous requirements of both field and laboratory testing environments; such as sunlight and high temperatures. The materials must be available in bulk sizes due to the possible requirement of a life-size model. This phantom will be used primarily to study the effects of laser exposures for near- and mid-infrared wavelengths.

Lasers that operate at 1540 nm are widely used by both government and civilian organizations. Military and law enforcement agencies¹ use this wavelength for range finders as well as laser designators. In addition, due to the non-ablative aspects of this wavelength on human skin, the medical field utilizes these infrared lasers for skin remodeling treatments². In this procedure, an Erbium:Glass laser stimulates collagen shrinkage and dermal wound healing while leaving the epidermis mostly intact. The result is smoother and tighter skin, while minimizing the possibility of scarring or permanent damage. This wavelength is considered “eye safe” because the exposure limits are larger than any other wavelength regime, but this nomenclature is discouraged in the ANSI Z136.1-2000 laser safety standard³. The standard for 1540 nm Maximum Permissible Exposure (MPE) for skin is 1 J/cm². Even though this wavelength has relatively large MPEs, this radiant exposure is commonly accessible with today’s higher-energy pulsed laser systems. Due to the various applications involving long-distance use of lasers at this wavelength, it is necessary to evaluate the risks of accidental exposure to the skin and eye from reflections.

Despite the many uses of lasers at the 1540 nm wavelength, there is relatively little data on the effects to human tissues. Skin is the largest organ in the body, and as such has more surface area which can be exposed to laser damage. It is composed of three layers; the epidermis, dermis and subcutaneous layers respectively. The average thickness of these three layers⁴ combined is approximately 2 mm, beyond the 1-mm depth⁴ of 1540 nm infrared laser penetration. Human

skin optical and thermal properties have been widely modeled, but there are surprisingly few references available from experimentation at this wavelength. Most experiments have been done using Yucatan and Yorkshire pig skin since it is very similar to human skin. Alexei Lukashev, et al^{5,6} and Cain, et al^{7,8} have done some work in this area using porcine (*Sus scrofa domestica*) test subjects, but they used a different spot size or duration parameters than this experiment. Pocock et al⁹ used the same parameters as this paper with hairless guinea pig (*Cavia porcellus*) subjects to find an MVL threshold. When creating this phantom, the Effective Dose (ED₅₀) levels determined by Cain, Lukashev and Pocock were used as the phantom objective [Table 2]

2. METHODS AND MATERIALS

2.1 Materials

Because of the unique field condition requirements that this phantom must endure, several materials were tested in order to find one that would give the best results. The first substance tested for the phantom was a two-part epoxy resin mixture called Poly-Sil 73 (Poly-Tek Develop. Corp., PA). It is a silicone rubber often used in the creation of molds and casts. The Poly-Sil provided a stable material that was the same density as human tissue. [Table 1] It had very low absorbance and scattering properties which allowed us to manipulate those properties as desired through the use of additional materials. The resin is formed by mixing two epoxy substances; Part A and Part B. The resin combination cures within six minutes to a semi-opaque finish. Resin can be purchased inexpensively in large quantities and has a long shelf-life, making it a preferred candidate for use in this phantom. One thing to consider when adding pigment or other substances is that both components of the rubber are hydrophobic. This will make incorporating any material with a water base very difficult.

Agar (Sigma Aldrich, MO) is another material that is used for creating phantoms. It is a dry powder comprised of seaweed polysaccharides and mixes with water to form a gel-like matrix. The amount of agar powder can be varied to alter the density of the material. It is readily available and can be easily stored since it comes in a powder form. However, it is fairly expensive compared to some of the other materials tested in this project.

The third substance tested was an animal protein gel (SIM-TEST™, Corbin Mfg., OR) that closely mimics the density of human tissue [Table 1]. SIM-TEST is most often used as a ballistic media in which studies are conducted on the ballistic effects of projectiles on human tissue. The gel can be prepared with almost no bubbles or aberrations being formed, and dries a translucent amber color. It has a high water content that facilitates the mixing of dyes and solutions into the gel, as well as helping to closely mimic the damage to human tissue. The medium is also fairly inexpensive and will remain viable for long periods of time if stored appropriately.

India Ink (KOH-I-NOOR Inc., NJ) is a water soluble dye used extensively in visible wavelength phantoms to increase photon absorbance rates. The absorption properties of the ink act as a substitute for melanin. It has a refractive index similar to melanin [Table 1] but it is a spherical shape where melanin is ovoid. While this ink is mainly used as an absorbing agent, it also has scattering properties due to its size and shape.

	Thickness (mm)	Density (g/cm ³)	MP (°C)	Thermal Conductivity (W/mK)	Refractive Index
Human Epidermis	.08 ¹⁰	1.2 ¹⁰	NA	.26 ¹¹	1.34 ¹²
Human Dermis	2.08 ¹⁰	1.2 ¹⁰	NA	.53 ¹¹	1.41 ¹²
Cured Resin	2.0	1.12	>340	.017 ¹³ (W/cm·s°C)	1.453
Pig Dermis (flank)	3.848 ¹⁴	--	NA	.511 (W/m°C)	1.361 ¹⁵
Pig Epidermis	.0795 ¹⁴	--	NA	--	--
Agar 4%	2.0	.995	93.4	.625 ¹⁶	1.333
SIMTEST	2.0	1.25	36-42	--	1.706
India Ink	.254 ¹⁷	1.03	NA	--	1.365 (500:1)
Melanin	.002 ¹⁸	1.4 ¹⁸	NA	.105 ¹⁹	1.4 ¹⁸

Table 1: Physical and Optical Properties.

2.2 Procedures

To prepare the epoxy resin phantom, the ink concentration is mixed into Part B making sure that it was well incorporated. An equal amount of Part A was then added, using the weight for measurement as opposed to volume (per product instructions). The mixture was again well mixed, then poured into 6 inch wide hexagonal mold, leaving a 2 cm thick sample. The samples were covered to prevent any debris from settling on them, and then allowed to harden.

To prepare the SIM-TEST phantom, large chunks were weighed and then cut into small pieces. The cubes were placed in a beaker over low heat, stirred until melted, and then immediately poured into a mold and allowed to solidify before adding a cover. Any additives were mixed in immediately after being poured to a 1-cm depth into the sample mold, which was 8 cm x 11 cm in size. This same mold was used for the agar samples also.

The agar mixture was made to form a 4% agar concentration. The desired amount of agar powder was added to water and heated until boiling, stirring constantly to avoid burning. In an effort to maximize the benefits of both materials, there were also several samples made that combined the agar and ballistic media together. For these items, the gel was melted and thoroughly mixed with the water media before adding the powder. The powder was added so that a ratio of two parts ballistic media to one part agar was formed. The ink was added immediately after the mixture was poured into the mold.

India Ink was added in various concentrations to each of the materials, and the samples were then run through a spectrometer (Cary 6000i, Varian Inc., CA). The purpose of this was to test whether or not a pigmenting material could alter the optical properties of these phantoms at this wavelength. The samples were created by first cutting 1 mm thick microscope slides into four sections. These pieces were then affixed between two more microscope slides to act as spacers; forming 1-mm, 2-mm, and 3-mm deep holders. Tape was placed along the bottom edge of the slides, and the phantom material was poured into this space. Once the material had solidified, another piece of tape was placed along the top to completely enclose the material. This reduced the chances of dehydration or material loss.

2.3 Measurements

Physical and optical properties of each material were obtained using standard laboratory techniques. Measurements were determined for both density and melting points. The refractive indexes of our materials were found using a 632 nm Nd:YAG laser and goniometer. (Physics Apparatus Research Inc.). The samples were placed 100 cm from a target and the refractive distance was marked on a white board. This is the same method for testing the refractive index that is used in several papers by Sardar¹⁸. This data was then used with equation (Equation 1) to determine the index of refraction for each sample. Due to its intense color, the India Ink was tested at a diluted strength of five hundred parts water to one part ink.

$$n = \frac{\sin(\alpha + \zeta_m)}{\sin(\alpha / 2)}$$

Equation 1: Where α is the apex angle; ζ_m is the minimum deviation or $\tan^{-1}(\text{refract. distance}/100\text{cm})$.

Prior to laser exposure, the prepared samples were marked with a grid of 1cm x 1cm squares and placed in the sample holder. Each sample contained 60-70 squares, depending on the surface finish. Any section that had previous damage or aberrations was not exposed. Each exposure was noted for any damage and the amount of energy delivered was raised or lowered accordingly. For damage assessment, immediate readings were taken and additional readings were taken anytime after 1 hour of being shot, since the damage did not change beyond that time frame. Readings required at least two out of three readers to confirm a perceptible change in the sample.

2.4 Laser Set-Up

The Er:Glass Megawatt laser was modified by Dr John Taboada²⁰ (Taboada Research Inst.) with a rotating Q-switch yielding 30-ns pulses of up to 3.5 joules per pulse at a wavelength of 1540 nm. Pulse duration was measured using an ET-3000 InGaAs Electro-Optics Technology, Inc. photodiode that was connected to a Tektronix TDS 220 Oscilloscope.

The beam was split with a 90/10 beam splitter and the Gaussian beam was measured with calibrated Molecron J25 probes. The energy measurements were made using a Molecron JD1000 energy meter. Visual alignment was made using a HeNe laser. [Figure 1] The sample holder was placed 24 inches from the last mirror leaving a 5-mm beam diameter at the tissue phantom surface.

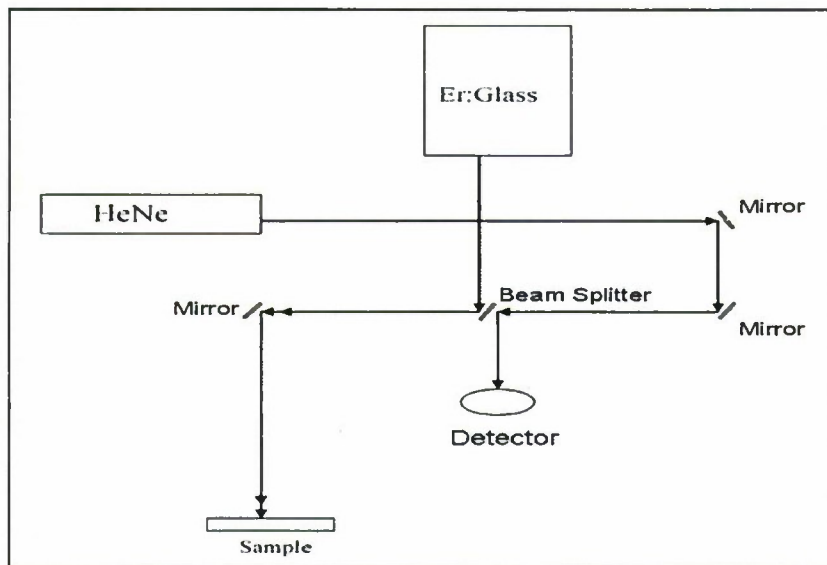


Figure 1: Schematic of laser set-up.

3. RESULTS

The SIM-TEST ballistic media was found to be a poor phantom material for the purpose of these laser exposures. Since the material is mostly water, it quickly dries out if left uncovered. Not only did that cause large cracks to form in the material, it altered the physical and optical properties as well. The largest problem associated with this material is its low melting point (36-37°C in these lab experiments) which would reduce its effectiveness during warm field testing conditions and result in lowered MVL values. In an effort to correct these problems, numerous other substances were added to the SIM-TEST; such as agar, glycerol, and dextrose. Dehydrated samples were also made by boiling the gel for an extended period of time before pouring it into the mold, thus reducing the water content by almost one-third. While these additives and procedures did aid in reducing the severity of dehydration and melting, they were not enough to make the gel a viable phantom material. This is unfortunate, since the lesions that formed upon exposure were similar in appearance to those seen in human skin.

Agar shared many of the same negative aspects as ballistic media, namely the high water content. In addition, it was not firm enough to withstand the rigors of handling without causing some breakage or tears. It was found to have a higher melting point than the ballistic gel (92°C).

The varying ink concentrations added to the samples appeared to have little to no effect on the ED₅₀s of agar, ballistic media, or resin. There was a slight increase to the material's absorption seen by the spectrometer; however, it was most likely due to the high water content of the ink rather than any properties of the ink particles.

The epoxy resin appeared to be the best suited for the purposes of this project. The high melting point and low evaporation rate of this substance made it a highly efficient material for this phantom. One drawback of this material is that mixing it incorporates air bubbles into the final product. Mixing the two parts in a vacuum was not feasible because the cure time is so short. Also, the mixture is viscous enough to make the removal of any air bubbles very slow and difficult. The transmission through the resin was approximately 12% and when the India Ink was added, this

transmission amount decreased accordingly. One of the other major drawbacks to this material is that it is highly hydrophobic. This made adding anything to the resin very difficult, especially water-based materials.

Upon initial exposure, the material showed a white spot [Figure 2a]; the intensity of which increased with energy. The high energy levels caused the material to become slightly raised at the center of the lesion; however this returned to normal after just a few moments. All damage appeared to be internal as there were no divots or abrasions on the surface. Within two minutes, the white marks disappeared, leaving a grey circle instead. Because of the fading properties of exposure damage, all of the immediate readings were taken exactly 5 seconds after being shot. The color of the grey circle also darkened with higher energies and only marks that were still observed more than an hour after exposure were listed as lesions [Figure 2b]. This is also evident that the lesions to the left side of the picture are much lighter than those in the center. One other note, as the ink concentration increased there was an additional circle of grey seen in many of the grid squares. The intensity and diameter of this circle increased with energy levels, and these marks were noticeable at levels well below the established ED_{50} s.

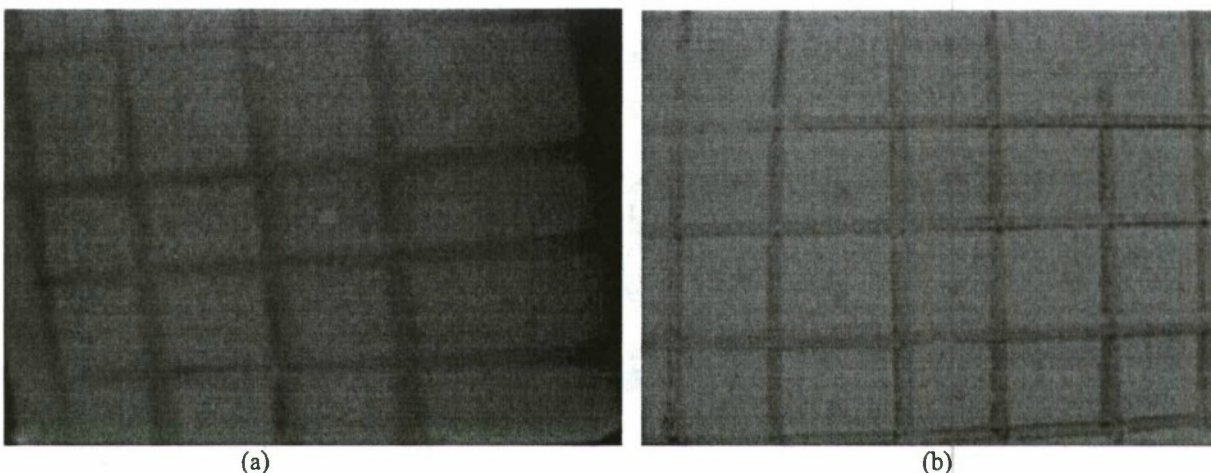


Figure 2: Resin damage marks after laser exposure. (a) Immediate (b) After 1 hour.

The damage observed in the epoxy resin phantom was also examined under a microscope. In Figure 3, the target area was magnified at 250x and shows the key components of the phantom. The brown lesion marks seems to be concentrated just below the surface and in the center 2 mm of the 5-mm spot. The air bubbles are visible in the damaged area as well as in the surrounding space. The India Ink particles are shown as the black marks. Figure 4 shows another epoxy resin sample at a magnification of 120x but this time the sample was exposed to 3 pulses to highlight the damage. Again, the brown damage is easily visible in the center 2 mm of the spot but this time the air bubbles are not readily noticeable in the damaged area.

4. DISCUSSION

4.1 Damage ED_{50} s

To find the ED_{50} we used Probit Analysis. The ED_{50} is the estimated dose which has a 50% probability of creating a visible lesion. This was computed using the EZ-Probit program designed by Dr. Clarence Cain, Gary Noojin and Capt. Lonnie Manning at Brooks City- Base in San Antonio, Texas²¹. It is a C++ program that operates on a personal computer and produces all the same output information as the SAS software. The ED_{50} was computed using a 95% confidence level.

The water-based phantoms were not able to withstand the environment required for this experiment. For all experiments with the Ballistic Media the ED_{50} s were below 2 J/cm^2 . This irradiance falls well below ED_{50} s reported in the literature

for guinea pigs and porcine studies [Table 2]. The low ED_{50} s are probably due to the high absorbance of water at 1540 nm and the low melting point of the gel.

This experiment found the preferred material of all researchers involved to be the epoxy resin. The ED_{50} for this material fell in between the values reported for other animal studies [Table 2]. This could be beneficial in the field of developing standards for the safe use of lasers since the phantom could be used as an alternative to live animal studies.

Material	MVL- ED_{50} (J/cm^2)
Ballistic Media (0.1% India Ink)	1.91
Epoxy Resin (0.1% India Ink)	3.82
Guinea Pig ⁹	3.0
Domestic Pig – (Lukashev) ^{5,6}	3.2
Yucatan Mini-Pig (Zohner) ²²	6.1

Table 2: Summary of ED_{50} Data

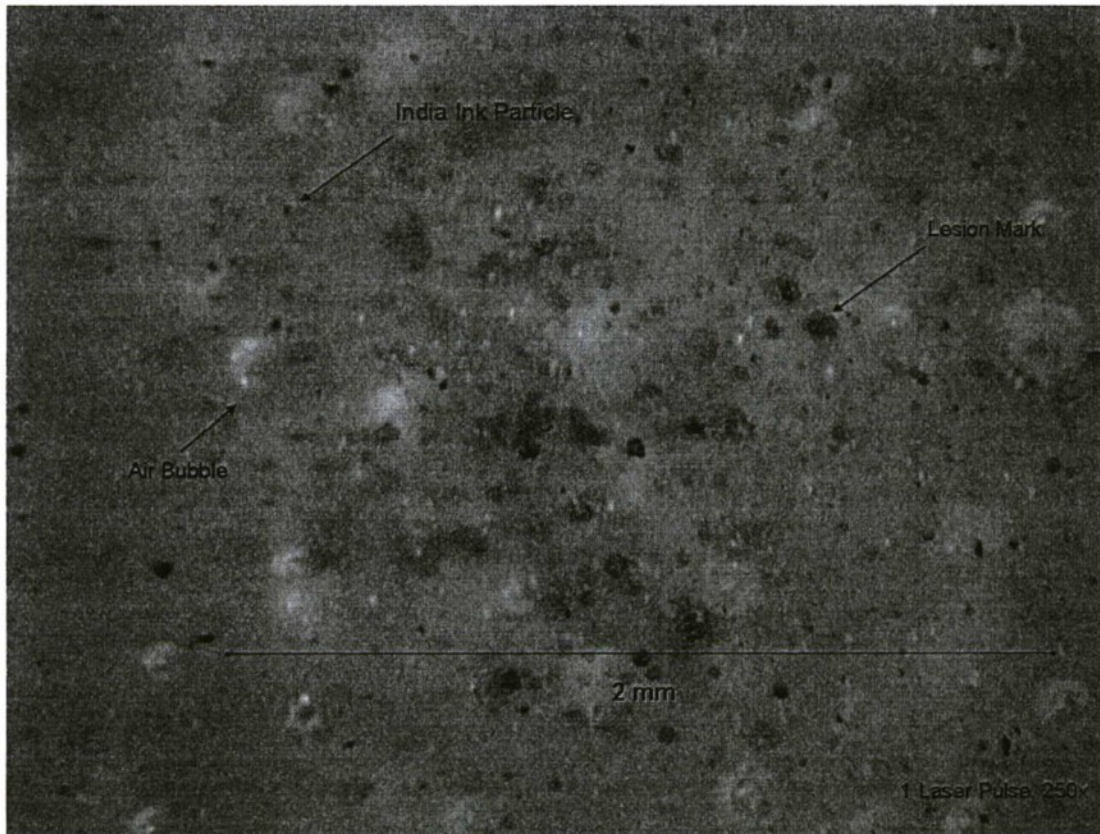


Figure 3: Laser Exposure Damage ($8.39 J/cm^2$) to Resin, viewed at 250x magnification.

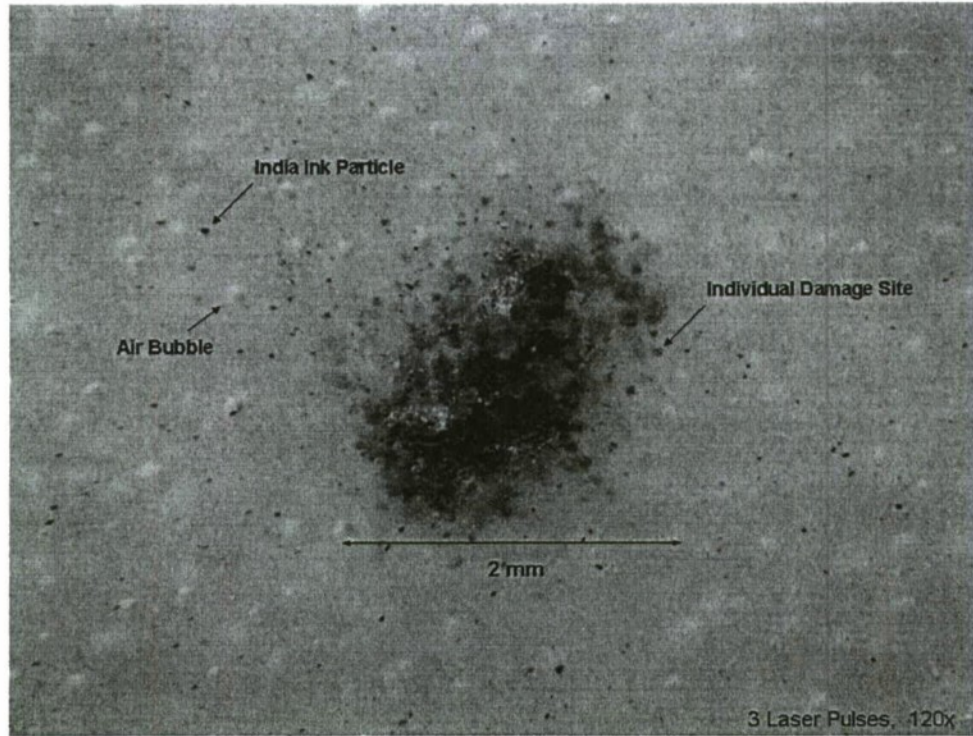


Figure 4: Laser Exposure Damage (6.29 J/cm^2) to resin viewed at 120x magnification. In this case, three pulses were shot into the same spot.

4.2 Damage Mechanism

The epoxy resin temperature rise was measured using thermocouples on the surface and was found to be minimal, approximately 0.02°C during exposures. This result, and a pulse duration of 30 ns, suggests that the mechanism for the damage observed from these laser exposures is not a thermal process. Additionally, when the damage is viewed under a microscope, no ablation of the resin surface is visible; instead there are brown marks in areas where bubbles were present before exposure. It seems possible then, that there is another mechanism for the damage seen, such as laser induced breakdown (LIB). Future studies can be conducted to determine if the damage occurs to the resin surrounding the air bubbles or to the air itself within the bubbles. The damage may be due to the optical or thermal properties of the phantom material or the focusing of the laser energy by the trapped air. It is interesting to note that while measuring the melting point for the resin there was no discoloration of the material, even in areas of direct contact with the heat source.

According to Walsh²³, plasma is generated when the irradiance exceeds $10^8 - 10^{10} \text{ W/cm}^2$. In our study the irradiance was $1.05 \times 10^8 \text{ W/cm}^2$ at the epoxy resin ED_{50} , which is near the threshold for plasma generation. Furthermore, equation (2) is used to determine the electric field amplitude²⁴, which is mainly based on the power density and is an indicator of dielectric breakdown when the amplitude reaches $2 \times 10^5 \text{ V/cm}$.

$$E = \left(\frac{2\Phi}{cn\epsilon_0} \right)^{1/2}$$

Equation 2: Electric Field Amplitude

Where:

n is the index of refraction of the epoxy resin phantom (1.5)

Φ is the power density ($1.05 \times 10^{12} \text{ W/m}^2$)

ϵ_0 is the permittivity of free space

c is the velocity of light

For the parameters in this study, the electric field intensity was $2.3 \times 10^5 \text{ V/cm}$, which again is right on the limit for dielectric breakdown. This is a sign that during exposures at our ED_{50} or above, the damage in our phantom was caused by LIB. Our result is also similar to Zohner's²² field intensity of $3.3 \times 10^7 \text{ V/m}$ at the surface of porcine skin.

5. CONCLUSION

Of the three materials tested, the resin appears to be the best substance for this phantom. It has the longest shelf-life, was the most durable, and is easily prepared. The damage is easily visible and occurs at similar irradiances that cause damage in animal models. We suggest that the damage mechanism at this wavelength and pulse duration is not due to thermal effects but rather laser induced breakdown. The ED_{50} for the epoxy resin falls between damage thresholds for porcine and guinea pig studies, which could make the phantom an alternative for damage studies. The phantom still needs to be tested at other infrared wavelengths to see how it compares to animal studies over a range of wavelengths.

The Ballistic Media and Agar samples did not meet the environmental conditions for this study, however, for different conditions a water based sample could be ideal as long as one remembers that water is highly absorbing at 1540 nm and any visible damage would probably be due to the water content and low melting point of the material; not the added absorbers.

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